Elements of mom4p1

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This document is freely distributed for ocean scientists interested in understanding the fundamentals of version 4.1 of the Modular Ocean Model (MOM). This document should be referenced as

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Information about how to download and run MOM4 can be found at the GFDL Flexible Modeling System (FMS) web site accessible from WWW.GFDL.NOAA.GOV.

Contents

Chapter One

Executive summary of mom4p1

MOM4p1 is a B-grid hydrostatic nonBoussinesq ocean model, with a Boussinesq option. This chapter provides an itemized summary of various code features. More discussion is provided in subsequent chapters. Note that items written in small capitals are new or substantially updated relative to MOM4.0.

1.1 GENERAL FEATURES

- GENERALIZED DEPTH AND PRESSURE BASED VERTICAL COORDINATES.
  - Full support for the quasi-horizontal coordinates

$$
\begin{aligned}
s &= z \\
s &= z^* = H\left(\frac{z-\eta}{H+\eta}\right) \\
s &= p \\
s &= p^* = p_{\mathrm{b}}^{o}\left(\frac{p-p_{\mathrm{a}}}{p_{\mathrm{b}}-p_{\mathrm{a}}}\right)
\end{aligned}
$$

  - Partial support for the terrain following coordinates

$$
\begin{aligned}
s &= \sigma^{(z)} = \frac{z-\eta}{H+\eta} \\
s &= \sigma^{(p)} = \frac{p-p_{\mathrm{a}}}{p_{\mathrm{b}}-p_{\mathrm{a}}}
\end{aligned}
$$

    There is presently no support for terrain following coordinates using neutral physics and sophisticated horizontal pressure gradient solvers.

- Generalized horizontal coordinates, with the tripolar grid of Murray (1996) supported in test cases. Other orthogonal grids have been successfully employed with MOM4 (e.g., Australian BLUELINK project).

- Parallel programming: mom4p1 follows the parallel programming approach of MOM4.0, and is written with arrays ordered (i, j, k) for straightforward processor domain decomposition. As with MOM4.0, mom4p1 relies on the GFDL Flexible Modeling System (FMS) infrastructure and superstructure code for computations on multiple parallel machines, with the code having been successfully run on dozens of computer platforms.

- EXPLICIT FREE SURFACE AND EXPLICIT BOTTOM PRESSURE SOLVER: MOM4 employs a split-explicit time stepping scheme where fast two-dimensional dynamics is sub-cycled within the slower three dimensional dynamics. The method follows ideas detailed in Chapter 12 of Griffies (2004), which are based on Killworth et al. (1991), Griffies et al. (2001). Chapter 7 in this document presents the details for mom4p1.

- Time stepping schemes: The time tendency for tracer and baroclinic velocity can be discretized two ways.
  - The first approach uses the traditional leap-frog method for the inviscid/dissipationless portion of the dynamics, along with a Robert Asselin time filter. This method is not fully supported, but is retained for legacy purposes.
  - The preferred method discretizes the time tendency with a two-level forward step, which eliminates the need to time filter. Tracer and velocity are staggered in time, thus providing second order accuracy in time. For certain model configurations, this scheme has been found to be twice as efficient as the leap-frog based scheme since one can take twice the time step with the two-level approach. Furthermore, without the time filtering needed with the leap-frog, the new scheme conserves total tracer to within numerical roundoff. This scheme is discussed in Griffies et al. (2005) and Chapter 7 of this document, and detailed in Chapter 12 of Griffies (2004).
- EQUATION OF STATE: The equation of state in mom4p1 follows the formulation of Jackett et al. (2006), where the coefficients from McDougall et al. (2003b) are updated to new empirical data.
- UPDATED FREEZING TEMPERATURE FOR FRAZIL: Accurate methods for computing the freezing temperature of seawater are provided by Jackett et al. (2006). These methods allow, in particular, for the computation of the freezing point at arbitrary depth, which is important for ice shelf modelling.
- CONSERVATIVE TEMPERATURE: mom4p1 time steps the conservative temperature described by McDougall (2003) to provide a measure of heat in the ocean. This variable is about 100 times more conservative than the traditional potential temperature variable. An option exists to set either conservative temperature or potential temperature prognostic, with the alternative temperature variable carried as a diagnostic tracer.
- PRESSURE GRADIENT CALCULATION: The pressure gradient calculation has been updated in mom4p1 to allow for the use of generalized vertical coordinates. A description of the formulation is given in Chapter 4. None of the sophisticated methods described by Shchepetkin and McWilliams (2002) are implemented in mom4p1, and so terrain following vertical coordinates may suffer from unacceptably large pressure gradients errors in mom4p1.
- Partial bottom steps: mom4p1 employs the partial bottom step technology of Pacanowski and Gnanadesikan (1998) to facilitate the representation of bottom topography. This approach is implemented for all of the vertical coordinates.

- TRACER ADVECTION: mom4p1 comes with the following array of tracer advection schemes.

  - First order upwind; this scheme is available with either time stepping scheme.
  - Second order centred differences; this scheme is unstable for the two-level scheme, so is only available for the three-level (leapfrog) time stepping.
  - Fourth order centred differences; this scheme is unstable for the two-level scheme, so is only available for the three-level (leapfrog) time stepping. This scheme assumes the grid is uniformly spaced (in metres), and so is less than fourth order accurate when the grid is stretched, in either the horizontal or vertical.
  - Sixth order centred differences; this scheme is unstable for the two-level scheme, so is only available for the three-level (leapfrog) time stepping. This scheme assumes the grid is uniformly spaced (in metres), and so is less than sixth order accurate when the grid is stretched, in either the horizontal or vertical. This scheme is experimental, and so *not* supported for general use.
  - Quicker scheme is third order upwind biased and based on the work of Leonard (1979). Holland et al. (1998) and Pacanowski and Griffies (1999) discuss implementations in ocean climate models. This scheme does not have flux limiters, so it is not monotonic. It is available with either time stepping scheme.
  - Quicker scheme in mom4p1 differs slightly from that in MOM3, and so the MOM3 algorithm has also been ported to mom4p1. It is available with either time stepping scheme.
  - Multi-dimensional third order upwind biased approach of Hundsdorfer and Trompert (1994), with Super-B flux limiters. The scheme is available in mom4p1 with either time stepping scheme.
  - Multi-dimensional third order upwind biased approach of Hundsdorfer and Trompert (1994), with flux limiters of Sweby (1984). It is available in mom4p1 with either time stepping scheme.
  - The second moment scheme of Prather (1986) has been implemented in mom4p1. It is available without limiters, or with the limiters of Merryfield and Holloway (2003). It is available in mom4p1 with either time stepping scheme.
  - The piece-wise parabolic method has been implemented in mom4p1. It is available in mom4p1 with either time stepping scheme.

- TRACER PACKAGES: mom4p1 comes with an array of tracer packages of use for understanding water mass properties and for building more sophisticated tracer capabilities, such as for ocean ecosystem models. These packages include the following.

- Idealized passive tracer module with internally generated initial conditions. These tracers are ideal for testing various advection schemes, for example, as well as to diagnose pathways of transport.
- An ideal age tracer, with various options for specifying the initial and boundary conditions.
- The OCMIP2 protocol tracers (CO_2, CFC, biotic).
- A new model of oceanic ecosystems and biogeochemical cycles is a state of the art model that considers 22 tracers including three phytoplankton groups, two forms of dissolved organic matter, heterotrophic biomass, and dissolved inorganic species for C, N, P, Si, Fe, $CaCO_3$ and O_2 cycling. The model includes such processes as gas exchange, atmospheric deposition, scavenging, N_2 fixation and water column and sediment denitrification, and runoff of C, N, Fe, O_2, alkalinity and lithogenic material. The phytoplankton functional groups undergo co-limitation by light, nitrogen, phosphorus and iron with flexible physiology. Loss of phytoplankton is parameterized through the size-based relationship of Dunne et al. (2005). Particle export is described through size and temperature based detritus formation and mineral protection during sinking with a mechanistic, solubility-based representation alkalinity addition from rivers, $CaCO_3$ sedimentation and sediment preservation and dissolution.

- Penetration of shortwave radiation as discussed in Sweeney et al. (2005).

- Horizontal friction: mom4p1 has a suite of horizontal friction schemes, such as Smagorinsky laplacian and biharmonic schemes described in Griffies and Hallberg (2000) and the anisotropic laplacian scheme from Large et al. (2001) and Smith and McWilliams (2003).

- Convection: There are various convective methods available for producing a gravitationally stable column. The scheme used most frequently at GFDL is that due to Rahmstorf (1993).

- NEUTRAL PHYSICS AND BOUNDARY REGIONS: There are new options available for treating neutral physics within boundary regions, as motivated from ideas proposed by Ferrari and McWilliams (2007). The mom4p1 formulation is given in Chapter 15

- FORM DRAG: MOM4p1 has an implementation of the transformed Eulerian mean approach of Greatbatch and Lamb (1990) and Greatbatch (1998), following the methods from Ferreira and Marshall (2006). Also, an alternative form drag scheme from Aiki et al. (2004) is available.

- TIDAL MIXING PARAMETERIZATION: The tidal mixing parameterization of Simmons et al. (2004) has been implemented as a means to parameterize the diapycnal mixing effects from breaking internal gravity waves, especially those waves influenced by rough bottom topography. Additionally, this scheme has been combined with that used by Lee et al. (2006), who discuss the importance of barotropic tidal energy on shelves for dissipating energy and producing tracer mixing. Chapter 13 presents the mom4p1 formulation.

- Other vertical mixing schemes: mom4p1 comes with an array of vertical mixing schemes, such as the following.
  - Constant background diffusivity proposed by Bryan and Lewis (1979).
  - Richardson number dependent scheme from Pacanowski and Philander (1981).
  - The KPP scheme from Large et al. (1994).
  - GENERAL OCEAN TURBULENCE MODEL (GOTM) (Umlauf et al., 2005), with numerous options, has been ported for use with mom4p1.
- UPDATE OF OVERFLOW SCHEMES: mom4p1 comes with various methods of use for parameterizing, or at least facilitating the representation of, dense water moving into the abyss. These schemes are documented in Chapter 16.
- REFINED OPEN BOUNDARY CONDITIONS MODULE: The open boundary conditions module has been updated for mom4p1 to facilitate its use for regional modelling. This scheme is documented in Chapter 11.
- UPDATED SPURIOUS MIXING DIAGNOSTIC: Griffies et al. (2000b) describe an empirical diagnostic method to diagnose the levels of mixing occurring in a model. This diagnostic required some upgrades to allow for the use of thickness weighting for time stepping the prognostic fields. This diagnostic is described in Chapter 18.
- STERIC SEA LEVEL DIAGNOSTIC: We compute the steric sea level diagnostically for the case when running a Boussinesq model. The formulation is given in Chapter 20.
- REVISED TEST CASES: All of the test cases have been revised as well as the addition of some new tests. Documentation of these tests is presented in Part 5 of this document.
- UPDATED FMS INFRASTRUCTURE AND PREPROCESSING TOOLS: As with all releases of mom4, it comes with updated infrastructure, preprocessing code, coupling code, etc. supported by an array of scientists and engineers at GFDL.

1.2 RELATING MOM4P1 TO MOM4.0

- Backward compatibility

  There is *no option* that will provide bitwise agreement between mom4p1 simulations and MOM4.0 simualations. Providing this feature was deemed too onerous on the development of mom4p1, in which case many of the algorithms were rewritten, reorganized, and modified.

  Nonetheless, some features have been preserved, with the aim to provide a reasonable path towards backward checking. In particular, the mom4p0 neutral physics algorithm has been retained, and indeed is recommended for production runs rather than the more recently developed mom4p1 altorithm (Chapter 15). Additionally, changes to KPP mentioned below are provided in the mom4p1 version of this module, with the MOM4.0 version ported to mom4p1.

- Bug fixes

  1. The shortwave penetration module in MOM4.0 failed to account for the undulating surface height when computing the attenuation of shortwave entering the ocean. For many cases this bug is of minor consequence. But when refining the vertical resolution, the surface height undulations must be accounted for when attentuating shortwave. Additionally, for general vertical coordinates, undulating depths are the norm, so the shortwave algorithm needed to be updated.
  2. The KPP vertical mixing scheme included many places where the vertical grid was assumed to be rigid and one dimensional. As for the shortwave, this code was originally developed for a rigid lid z-model. When generalizing to free surface, partial bottom steps, and generalized vertical, the vertical grid becomes a dynamic three dimensional array, which required some modifications to the code.

- General cleanup and additions

  1. Numerous additional diagnostic features
  2. Basic code clean up with bit more tidy code style in most places
  3. Thoroughly updated documentation of mom4p1 as a complement to the MOM4 Technical Guide of Griffies et al. (2004)

- Unresolved issues and minimally tested features

  1. The open boundary conditions (Chapter 11) have been tested only with depth-based vertical coordinates, with emphasis on geopotential. In principle, the code should work transparently for the $z*$ and $z^{(\sigma)}$ coordinates as well, since the barotropic algorithms are all the same. The OBCs with pressure based vertical coordinates, however, will need to be revisited.
  2. As stated in Section 1.1, there is only partial support for the terrain following vertical coordinates in mom4p1. There are no active research applications at GFDL with this coordinate, so its features are less developed than the quasi-horizontal general vertical coordinates.

Chapter Two

Synopsis of mom4p1

The purpose of this document is to detail the formulation, methods, and selected SGS parameterizations of mom4p1. This document complements many of the discussions in the MOM3 Manual of Pacanowski and Griffies (1999), the MOM4 Technical Guide of Griffies et al. (2004), and the monograph by Griffies (2004).

The equations and methods of mom4p1 are based on the hydrostatic and non-Boussinesq equations of the ocean along with a selection of subgrid scale (SGS) parameterizations. The model is written with rudimentary general vertical coordinate capabilities employing a quasi-Eulerian algorithm. Notably, this approach precludes it from running as a traditional isopycnal layered model, which generally use quasi-Lagrangian algorithms. Nonetheless, the generalized vertical coordinate features of mom4p1 distinguish it most noticeably from MOM4.0. The purpose of this chapter is to summarize the basic elements of mom4p1. Features new relative to MOM4.0 are highlighted in smallcaps.

2.1 WHAT IS MOM?

The Modular Ocean Model (MOM) is a numerical representation of the ocean's hydrostatic primitive equations. It is designed primarily as a tool for studying the ocean climate system. Additionally, MOM has been used in regional and coastal applications, with many new features in mom4p1 aimed at supporting this work. The model is developed by researchers from around the world, with the main algorithm development and software engineering provided by NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). The model is freely available via
`http://www.gfdl.noaa.gov/fms`

MOM evolved from numerical ocean models developed in the 1960's-1980's by Kirk Bryan and Mike Cox at GFDL. Most notably, the first internationally released and supported primitive equation ocean model was developed by Mike Cox (Cox (1984)). It cannot be emphasized enough how revolutionary it was in 1984 to freely release, support, and document code for use in numerical ocean climate modeling. The Cox-code provided scientists worldwide with a powerful tool to investigate basic and applied questions about the ocean and its interactions with other components of the climate system. Previously, rational investigations of such questions by most scientists were limited to restrictive idealized models and analytical methods. Quite simply, the Cox-code started what has today become a right-of-passage for every high-end numerical model of dynamical earth systems.

Upon the untimely passing of Mike Cox in 1990, Ron Pacanowski, Keith Dixon, and Tony Rosati rewrote the Cox code with an eye on new ideas of modular programming using Fortran 77. The result was the first version of MOM (Pacanowski et al. (1991)). Version 2 of MOM (Pacanowski (1995)) introduced the memory window idea, which was a generalization of the vertical-longitudinal slab approach used in the Cox-code and MOM1. Both of these methods were driven by the desires of modelers to run large experiments on machines with relatively small memories. The memory window provided enhanced flexibility to incorporate higher order numerics, whereas slabs used in the Cox-code and MOM1 restricted the numerics to second order. MOM3 (Pacanowski and Griffies (1999)) even more fully exploited the memory window with a substantial number of physics and numerics options.

The Cox-code and each version of MOM came with a manual. Besides describing the elements of the code, these manuals aimed to provide transparency to the rationale underlying the model's numerics. Without such, the model could in many ways present itself as a black box, thus greatly hindering its utility to the scientific researcher. This philosophy of documentation saw its most significant realization in the MOM3 Manual, which reaches to 680 pages. The present document is written with this philosophy in mind, yet allows itself to rely somewhat on details provided in the previous manuals as well as theoretical discussions given by Griffies (2004).

The most recent version of MOM is version 4. The origins of MOM4 date back to a transition from vector to parallel computers at GFDL, starting in 1999. Other models successfully made the transition some years earlier (e.g., The Los Alamos Parallel Ocean Program (POP) and the OCCAM model from Southampton, UK). New computer architectures generally allow far more memory than previously available, thus removing many of the reasons for the slabs and memory window approaches used in earlier versions of MOM. Hence, we concluded that the memory window should be jettisoned in favor of a straightforward horizontal 2D domain decomposition. Thus began the project to redesign MOM for use on parallel machines.

2.2 FIRST RELEASE OF MOM4.0: OCTOBER 2003

As may be anticipated, when physical scientists aim to rewrite code based on software engineering motivations, more than software issues are addressed. During the writing of MOM4, numerous algorithmic issues were also addressed, which added to the development time. Hence, the task of rewriting MOM3 into MOM4.0 took roughly four years to complete.

2.3 FIRST RELEASE OF MOM4P1: LATE 2007

Griffies spent much of 2005 in Hobart, Australia as a NOAA representative at the CSIRO Marine and Atmospheric Research Laboratory, as well as with researchers at the University of Tasmania. This period saw focused work to upgrade MOM4 to include certain features of generalized vertical coordinates. An outline of these, and other features, is given in the following sections.

By allowing for the use of a suite of vertical coordinates, mom4p1 is algorithmically more flexible than any previous version of MOM. This work, however, did not fundamentally alter the overall computational structure relative to the last release of MOM4.0 (the mom4p0d release in May 2005). In particular, mom4p1 is closer in "look and feel" to mom4p0d than mom4p0a is to MOM3.1. Given this similarity, it was decided to retain the MOM4 name for the mom4p1 release, rather switch to MOM5. However, it is notable that the nomenclature uses the smaller case "mom4p1", which is indicative of the more experimental nature of the code than the MOM4.0 version. That is, mom4p1, with its multitude of extended options, should be considered an experimental code. This situation then encourages a more critical examination of simulation integrity from the user than warranted with the more mature algorithms in MOM4.0.

2.4 FUNDAMENTALS OF MOM4P1

In this section, we outline fundamental features of mom4p1; that is, features that are always employed when using the code.

- GENERALIZED VERTICAL COORDINATES: Various vertical coordinates have been implemented in mom4p1. We have focused attention on vertical coordinates based on functions of depth or pressure, which means in particualar that mom4p1 *does not* support thermodynamic or isopycnal based vertical coordinates.*

  The following list summarizes the coordinates presently implemented in mom4p1. Extensions to other vertical coordinates are straightforward, given the framework available for the coordinates already present. Full details of the vertical coordinates are provided in Chapter 6.

  - Geopotential coordinate as in MOM4.0, including the undulating free surface at $z = \eta$ and bottom partial cells approximating the bottom topography at $z = -H$
  $$s = z. \tag{2.1}$$
  - Quasi-horizontal rescaled height coordinate of Stacey et al. (1995) and Adcroft and Campin (2004)
  $$\begin{aligned} s &= z^{*} \\ &= H\left(\frac{z-\eta}{H+\eta}\right). \end{aligned} \tag{2.2}$$
  - Depth based terrain following "sigma" coordinate, popular for coastal applications
  $$\begin{aligned} s &= \sigma^{(z)} \\ &= \frac{z-\eta}{H+\eta}. \end{aligned} \tag{2.3}$$

*The Hallberg Isopycnal Model (HIM) is available from GFDL for those wishing to use layered models. HIM is a Fortran code that is fully supported by GFDL scientists and engineers. Information about HIM is available at `http://www.gfdl.noaa.gov/fms/`.

– Pressure coordinate

$$s = p \tag{2.4}$$

was shown by Huang et al. (2001), DeSzoeke and Samelson (2002), Marshall et al. (2004), and Losch et al. (2004) to be a useful way to transform Boussinesq z-coordinate models into nonBoussinesq pressure coordinate models.

– Quasi-horizontal rescaled pressure coordinate

$$\begin{aligned} s &= p^* \\ &= p_{\mathrm{b}}^{o} \left(\frac{p - p_{\mathrm{a}}}{p_{\mathrm{b}} - p_{\mathrm{a}}} \right), \end{aligned} \tag{2.5}$$

where p_{a} is the pressure applied at the ocean surface from the atmosphere and/or sea ice, p_{b} is the hydrostatic pressure at the ocean bottom, and p_{b}^{o} is a time independent reference bottom pressure.

– Pressure based terrain following coordinate

$$\begin{aligned} s &= \sigma^{(p)} \\ &= \left(\frac{p - p_{\mathrm{a}}}{p_{\mathrm{b}} - p_{\mathrm{a}}} \right). \end{aligned} \tag{2.6}$$

Note the following points:

– All depth based vertical coordinates implement the volume conserving, Boussinesq, ocean primitive equations.

– All pressure based vertical coordinates implement the mass conserving, nonBoussinesq, ocean primitive equations.

– There has little effort focused on reducing pressure gradient errors in the terrain following coordinates (Section 4.2). Researchers intent on using terrain following coordinates may find it necessary to implement one of the more sophisticated pressure gradient algorithms available in the literature, such as that from Shchepetkin and McWilliams (2002).

– Use of neutral physics parameterizations (Section 5.2.3 and Chapter 15) with terrain following coordinates is not recommended with the present implementation. There are formulation issues which have not been addressed, since the main focus of neutral physics applications at GFDL centres on vertical coordinates which are quasi-horizontal.

– Most of the vertical coordinate dependent code is in the

`mom4/ocean_core/ocean_thickness_mod`

module, where the thickness of a grid cell is updated according to the vertical coordinate choice. The developer intent on introducing a new vertical coordinate may find it suitable to emulate the steps taken in this module for other vertical coordinates. The remainder of the model code is generally transparent to the specific choice of vertical coordinate, and such has facilitated a straightforward upgrade of the code from MOM4.0 to mom4p1.

- Generalized horizontal coordinates: mom4p1 is written using generalized horizontal coordinates. The formulation in this document follows this approach as well. For global ocean climate modelling, mom4p1 comes with test cases (the OM3 test cases) using the tripolar grid of Murray (1996). Other orthogonal grids have been successfully employed with MOM4.0.

  Code for reading in the grid and defining mom4 specific grid factors is found in the module

  `mom4/ocean_core/ocean_grids_mod`.

  MOM comes with preprocessing code suitable for generating grid specification files of various complexity, including the Murray (1996) tripolar grid. Note that the horizontal grid in mom4 is static (time independent), whereas the vertical grid is generally time dependent, hence the utility in separating the horizontal from the vertical grids.

- Parallel programming: mom4p1 follows the parallel programming approach of MOM4.0, and is written with arrays ordered (i, j, k) for straightforward processor domain decomposition.

- EXPLICIT FREE SURFACE AND EXPLICIT BOTTOM PRESSURE SOLVER: MOM4 employs a split-explicit time stepping scheme where fast two-dimensional dynamics is sub-cycled within the slower three dimensional dynamics. The method follows ideas detailed in Chapter 12 of Griffies (2004), which are based on Killworth et al. (1991), Griffies et al. (2001). Chapter 7 presents the details for mom4p1, and the code is on the module

  `mom4/ocean_core/ocean_barotropic_mod`.

- Time stepping schemes: The time tendency for tracer and baroclinic velocity can be discretized two ways. (1) The first approach uses the traditional leap-frog method for the inviscid/dissipationless portion of the dynamics, along with a Robert-Asselin time filter. (2) The preferred method discretizes the time tendency with a two-level forward step, which eliminates the need to time filter. Tracer and velocity are staggered in time, thus providing second order accuracy in time. For certain model configurations, this scheme has been found to be twice as efficient as the leap-frog based scheme since one can take twice the time step with the two-level approach. Furthermore, without the time filtering needed with the leap-frog, the new scheme conserves total tracer to within numerical roundoff. This scheme is discussed in Griffies et al. (2005) and Chapter 7 of this document, and detailed in Chapter 12 of Griffies (2004). The code implementing these ideas in mom4p1 can be found in

  `mom4/ocean_core/ocean_velocity_mod`

  `mom4/ocean_tracers/ocean_tracer_mod`

- Time stepping the Coriolis force: As discussed in Chapter 10, there are various methods available for time stepping the Coriolis force on the B-grid used in mom4. The most commonly used method for global climate simulations at GFDL is the semi-implicit approach in which half the force is evaluated at the present time and half at the future time.

- EQUATION OF STATE: The equation of state in mom4p1 follows the formulation of Jackett et al. (2006), where the coefficients from McDougall et al. (2003b) are updated to new empirical data. The code for computing density is found in the module

  `mom4/ocean_core/ocean_density_mod`.

- CONSERVATIVE TEMPERATURE: mom4p1 time steps the conservative temperature described by McDougall (2003) to provide a measure of heat in the ocean. This variable is about 100 times more conservative than the traditional potential temperature variable. An option exists to set either conservative temperature or potential temperature prognostic, with the alternative temperature variable carried as a diagnostic tracer. This code for computing conservative temperature is within the module

  `mom4/ocean_tracers/ocean_tempsalt_mod`.

- PRESSURE GRADIENT CALCULATION: The pressure gradient calculation has been updated in mom4p1 to allow for the use of generalized vertical coordinates. A description of the formulation is given in Chapter 4, and the code is in the module

  `mom4/ocean_core/ocean_pressure_mod`.

  Notably, none of the sophisticated methods described by Shchepetkin and McWilliams (2002) are implemented in mom4p1, and so terrain following vertical coordinates may suffer from unacceptably large pressure gradients errors in mom4p1. Researchers are advised to perform careful tests prior to using these coordinates.

- Partial bottom steps: mom4p1 employs the partial bottom step technology of Pacanowski and Gnanadesikan (1998) to facilitate the representation of bottom topography, with the code in the module

  `mom4/ocean_core/ocean_topog_mod`.

2.5 TRACER FEATURES

Here, we outline some of the features available for tracers in mom4p1.

- Tracer advection: mom4p1 comes with the following array of tracer advection schemes.
  - First order upwind; this scheme is available with either time stepping scheme.
  - Second order centred differences; this scheme is unstable for the two-level scheme, so is only available for the three-level (leapfrog) time stepping.
  - Fourth order centred differences; this scheme is unstable for the two-level scheme, so is only available for the three-level (leapfrog) time stepping. This scheme assumes the grid is uniformly spaced (in metres), and so is less than fourth order accurate when the grid is stretched, in either the horizontal or vertical.

- Sixth order centred differences; this scheme is unstable for the two-level scheme, so is only available for the three-level (leapfrog) time stepping. This scheme assumes the grid is uniformly spaced (in metres), and so is less than sixth order accurate when the grid is stretched, in either the horizontal or vertical. This scheme is experimental, and so *not* supported for general use.
- Quicker scheme is third order upwind biased and based on the work of Leonard (1979). Holland et al. (1998) and Pacanowski and Griffies (1999) discuss implementations in ocean climate models. This scheme does not have flux limiters, so it is not monotonic. It is available with either time stepping scheme.
- Quicker scheme in mom4p1 differs slightly from that in MOM3, and so the MOM3 algorithm has also been ported to mom4p1. It is available with either time stepping scheme.
- Multi-dimensional third order upwind biased approach of Hundsdorfer and Trompert (1994), with Super-B flux limiters.[*] The scheme is available in mom4p1 with either time stepping scheme.
- Multi-dimensional third order upwind biased approach of Hundsdorfer and Trompert (1994), with flux limiters of Sweby (1984).[†] It is available in mom4p1 with either time stepping scheme.
- The second order moment scheme of Prather (1986) has been implemented in mom4p1. It can be run without limiters or with the limiters suggested by Merryfield and Holloway (2003). It is available in mom4p1 with either time stepping scheme.
- The piece-wise parabolic method has been implemented in mom4p1. It is available in mom4p1 with either time stepping scheme.

Both of the MIT-based schemes are non-dispersive, preserve shapes in three dimensions, and preclude tracer concentrations from moving outside of their natural ranges in the case of a purely advective process. They are modestly more expensive than the Quicker scheme, and it do not significantly alter the simulation relative to Quicker in those regions where the flow is well resolved. The Sweby limiter code was used for the ocean climate model documented by Griffies et al. (2005).

The code for tracer advection schemes are in the module

`mom4/ocean_tracers/ocean_tracer_advect_mod`.

- TRACER PACKAGES: mom4p1 comes with an array of tracer packages of use for understanding water mass properties and for building more sophisticated tracer capabilities, such as from ecosystem models. These packages include the following.

[*]This scheme was ported to mom4 by Alistair Adcroft, based on his implementation in the MITgcm. The online documentation of the MITgcm at `http://mitgcm.org` contains useful discussions and details about this advection scheme.

[†]This scheme was ported to mom4 by Alistair Adcroft, based on his implementation in the MITgcm. The online documentation of the MITgcm at `http://mitgcm.org` contains useful discussions and details about this advection scheme.

- Idealized passive tracer module with internally generated initial conditions. These tracers are ideal for testing various advection schemes, for example, as well as to diagnose pathways of transport.
- An ideal age tracer, with various options for specifying the initial and boundary conditions.
- The OCMIP2 protocol tracers (CO_2, CFC, biotic).
- A new model of oceanic ecosystems and biogeochemical cycles is a state of the art model that considers 22 tracers including three phytoplankton groups, two forms of dissolved organic matter, heterotrophic biomass, and dissolved inorganic species for C, N, P, Si, Fe, $CaCO_3$ and O_2 cycling. The model includes such processes as gas exchange, atmospheric deposition, scavenging, N_2 fixation and water column and sediment denitrification, and runoff of C, N, Fe, O_2, alkalinity and lithogenic material. The phytoplankton functional groups undergo co-limitation by light, nitrogen, phosphorus and iron with flexible physiology. Loss of phytoplankton is parameterized through the size-based relationship of Dunne et al. (2005). Particle export is described through size and temperature based detritus formation and mineral protection during sinking with a mechanistic, solubility-based representation alkalinity addition from rivers, $CaCO_3$ sedimentation and sediment preservation and dissolution.

The modules for these tracers are in the directory

`mom4/ocean_tracers`.

- UPDATED FREEZING TEMPERATURE FOR FRAZIL: Accurate methods for computing the freezing temperature of seawater are provided by Jackett et al. (2006). These methods allow, in particular, for the computation of the freezing point at arbitrary depth, which is important for ice shelf modelling. These methods have been incorporated into the frazil module

  `mom4/ocean_tracers/ocean_frazil_mod`,

  with heating due to frazil formation treated as a diagnostic tracer.

- Penetration of shortwave radiation: Sweeney et al. (2005) compile a seasonal climatology of chlorophyll based on measurements from the NASA SeaWIFS satellite. They used this data to develop two parameterizations of visible light absorption based on the optical models of Morel and Antoine (1994) and Ohlmann (2003). The two models yield quite similar results when used in global ocean-only simulations, with very small differences in heat transport and overturning.

  The Sweeney et al. (2005) chlorophyll climatology is available with the distribution of mom4. The code available in the module

  `mom4/ocean_param/sources/ocean_shortwave_mod`

  implements the optical model of Morel and Antoine (1994). This method for attenuating shortwave radiation was employed in the CM2 coupled climate model, as discussed by Griffies et al. (2005). In mom4p1, we updated the algorithm relative to MOM4.0 by including the time dependent nature of the vertical position of a grid cell. The MOM4.0 implementation used the vertical position appropriate only for the case of a static ocean free surface.

There is an additional shortwave penetration module prepared at CSIRO Marine and Atmospheric Research in Australia. This module makes a few different assumptions and optimizations. It is supported in mom4p1 by CSIRO researchers.

2.6 SUBGRID SCALE PARAMETERIZATIONS

Here, we outline some features of the subgrid scale parameterizations available in mom4p1.

- Horizontal friction: mom4p1 has a suite of horizontal friction schemes, such as Smagorinsky laplacian and biharmonic schemes described in Griffies and Hallberg (2000) and the anisotropic laplacian scheme from Large et al. (2001) and Smith and McWilliams (2003). Code for these schemes is found in the modules

  `mom4/ocean_param/mixing/ocean_lapgen_friction_mod`

  `mom4/ocean_param/mixing/ocean_bihgen_friction_mod`.

- Convection: There are various convective methods available for producing a gravitationally stable column, with the code found in the module

  `mom4/ocean_param/mixing/ocean_convect_mod`.

  The scheme used most frequently at GFDL is that due to Rahmstorf (1993).

- NEUTRAL PHYSICS AND BOUNDARY REGIONS: There are new options available for treating neutral physics within boundary regions, as motivated from ideas proposed by Ferrari and McWilliams (2007). A discussion of these ideas is given in Chapter 15 of this document, and the code is available in the module

  `mom4/ocean_param/mixing/ocean_nphysics_mom4p1_mod`,

  with the MOM4.0 methods remaining in

  `mom4/ocean_param/mixing/ocean_nphysics_mom4p0_mod`.

- FORM DRAG: MOM4p1 has an implementation of the transformed Eulerian mean approach of Greatbatch and Lamb (1990) and Greatbatch (1998), following the methods from Ferreira and Marshall (2006). This scheme is coded in the module

  `mom4/ocean_param/mixing/ocean_nphysics_mod`.

  Also, an alternative form drag scheme from Aiki et al. (2004) is available in the module

  `mom4/ocean_param/mixing/ocean_form_drag_mod`.

- TIDAL MIXING PARAMETERIZATION: The tidal mixing parameterization of Simmons et al. (2004) has been implemented as a means to parameterize the diapycnal mixing effects from breaking internal gravity waves, especially those waves influenced by rough bottom topography. Additionally, this scheme has been combined with that used by Lee et al. (2006), who discuss the importance of barotropic tidal energy on shelves for dissipating energy and producing tracer mixing. Chapter 13 presents the model formulation, and

  `mom4/ocean_param/mixing/ocean_vert_tidal_mod`

  contains the code.

- Other vertical mixing schemes: mom4p1 comes with an array of vertical mixing schemes, such as the following.

  - Constant background diffusivity proposed by Bryan and Lewis (1979), with code in

    `mom4/ocean_param/mixing/ocean_vert_mix_mod`

  - Richardson number dependent scheme from Pacanowski and Philander (1981), with code in

    `mom4/ocean_param/mixing/ocean_vert_pp_mod`

  - The KPP scheme from Large et al. (1994), with code in

    `mom4/ocean_param/mixing/ocean_vert_kpp_mod`

  - GENERAL OCEAN TURBULENCE MODEL (GOTM): Coastal simulations require a suite of vertical mixing schemes beyond those available in MOM4.0. GOTM (Umlauf et al., 2005) is a public domain Fortran90 free software supported by European scientists and used by a number of coastal ocean modellers (see `http://www.gotm.net/`). GOTM includes many of the most sophisticated turbulence closure schemes available today. It is continually upgraded and will provide users of mom4p1 with leading edge methods for computing vertical diffusivities and vertical viscosities. GOTM has been coupled to mom4p1 by scientists at CSIRO in Australia in collaboration with German and GFDL scientists. The mom4p1 wrapper for GOTM is

    `mom4/ocean_param/mixing/ocean_vert_gotm_mod`

    with the GOTM source code in the directory

    `mom4/ocean_param/gotm`.

- UPDATE OF OVERFLOW SCHEMES: mom4p1 comes with various methods of use for parameterizing, or at least facilitating the representation of, dense water moving into the abyss. These schemes are documented in Chapter 16, with the following modules implementing these methods

  `mom4/ocean_param/mixing/ocean_sigma_transport_mod`

  `mom4/ocean_param/mixing/ocean_mixdownslope_mod`

  `mom4/ocean_param/sources/ocean_overflow_mod`

  `mom4/ocean_param/sources/ocean_overexchange_mod`.

2.7 MISCELLANEOUS FEATURES

Here, we outline some miscellaneous features of mom4p1.

- REFINED OPEN BOUNDARY CONDITIONS MODULE: The open boundary conditions module has been updated for mom4p1 to facilitate its use for regional modelling. This code is found in the module

  `mom4/ocean_core/ocean_obc_mod`.

  and is documented in Chapter 11.

- UPDATED SPURIOUS MIXING DIAGNOSTIC: Griffies et al. (2000b) describe an empirical diagnostic method to diagnose the levels of mixing occurring in a model. This diagnostic required some upgrades to allow for the use of thickness weighting for time stepping the prognostic fields (see Chapter 18, especially Section 18.3). This code is available in the module

  `mom4/ocean_diag/ocean_tracer_diag_mod`.

- STERIC SEA LEVEL DIAGNOSTIC: We now compute the steric sea level diagnostically for the case when running a Boussinesq model. The formulation is given in Chapter 20.

- REVISED TEST CASES: All of the test cases have been revised as well as the addition of some new tests. As in MOM4.0, the tests are **not sanctioned for their physical realism.** Instead, they are provided for computations and numerical evaluation, and as starting points for those wishing to design and implement their own research models.

- UPDATED FMS INFRASTRUCTURE AND PREPROCESSING TOOLS: As with all releases of mom4, it comes with updated infrastructure, preprocessing code, coupling code, etc. supported by an array of scientists and engineers at GFDL.

2.8 SHORT BIBLIOGRAPHY OF MOM4 DOCUMENTS

The following is an incomplete list of documents that may prove useful for those wishing to learn more about the mom4 code, and some of its uses at GFDL.

- The MOM3 Manual of Pacanowski and Griffies (1999) continues to contain useful discussions about issues that remain relevant for mom4.
- The MOM4 Technical Guide of Griffies et al. (2004) aims to document the MOM4.0 code and its main features.
- The present document, Griffies (2007), presents the fundamental formulation and model algorithms of use for the generalized vertical coordinate code mom4p1.
- The monograph by Griffies (2004) presents a pedagogical treatment of many areas relevant for ocean climate modellers.

- The paper by Griffies et al. (2005) provides a formulation of the ocean climate model used in the GFDL CM2 climate model for the study of global climate variability and change. The ocean code is based on MOM4.0.
- The paper by Gnanadesikan et al. (2006a) describes the ocean simulation characteristics from the coupled climate model CM2.
- The paper by Delworth et al. (2006) describes the coupled climate model CM2.
- The paper by Wittenberg et al. (2006) focuses on the tropical simulations in the CM2 coupled climate model.
- The paper by Stouffer et al. (2006) presents some idealized climate change simulations with the coupled climate model CM2.

2.9 THE FUTURE OF MOM

MOM has had a relatively long and successful history. The release of mom4p1 represents a major step at GFDL to move into the world of generalized vertical coordinate models. It is anticipated that mom4p1 will be used at GFDL and abroad for many process, coastal, regional, and global studies. It is, quite simply, the most versatile of the MOM codes produced to date.

Nonetheless, there are many compelling reasons to move even further along the generalization path, in particular to include isopycnal layered models in the same code base as z-like vertical coordinates. As discussed in Griffies et al. (2000a), there remain many systematic problems with each vertical coordinate class, and such warrants the development of a single code base that can examine these issues in a controlled setting.

GFDL employs the developers of three of the world's most successful ocean model codes: (1) Alistair Adcroft, who developed the MITgcm, which has non-hydrostatic and hydrostatic options; (2) Bob Hallberg, who developed the Hallberg Isopycnal Model, which has been used for process studies and global coupled modelling, and (3) Stephen Griffies, who has been working on MOM development. A significant step forward in ocean model code will be found by merging various features of the MITgcm, HIM, and MOM. Therefore, Adcroft, Griffies, and Hallberg have each agreed to evolve their efforts, starting in 2007, towards the goal of producing a GFDL Unified Ocean Model. The name of this model is yet to be determined.